Microstructure Evolution and Pore Formation Mechanism of Porous TiAl_3 Intermetallics via Reactive Sintering

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Abstract Porous TiAl_3 intermetallics were fabricated through vacuum reactive sintering from Ti–75Al at.% elemental powder mixture. The phase compositions, expansion behaviors, pore characteristics and microstructure evolution of TiAl_3 intermetallics were investigated, and the pore formation mechanism was also proposed. It was found that the actual temperature of compacts showed an acute climb from 668 to 1244 °C in 166s, while the furnace temperature maintained the linear growth of 5 °C/min, which indicated that an obvious thermal explosion (TE) reaction occurred during sintering, and only single-phase TiAl_3 intermetallic was synthesized in TE products. The open porosity increased from 22.2 (green compact) to 32.8% after reactive diffusion sintering at 600 °C and rised to 58.7% after TE, then decreased to 51.2% after high-temperature homogenization at 1100 °C. Therefore, TE reaction is the dominated pore formation mechanism of porous TiAl_3 intermetallics. The pore evolution in porous TiAl_3 intermetallics occurred by the following mechanisms: certain intergranular pores remained among powder particles of green compact, then low-temperature sintering resulted in a further increase in porosity due to the Kirkendall effect. Moreover, TE reaction gave rise to a dramatic volume expansion because of the rapid increase in temperature, and high-temperature sintering caused densification and a slight shrinkage.

KEY WORDS: Intermetallics; Porous materials; Powder metallurgy; Reaction synthesis; Thermal explosion synthesis

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1 Introduction

Intermetallics are potential functional and structural material with a mixture of metallic and covalent bonds enabling their excellent properties such as high melting point, good strength and oxidation resistance at elevated temperature [1]. The combination of these properties make intermetallics suitable for industrial applications in automotive industry and energy generation [2–4]. In particular, Al-based intermetallic compounds attract much attention due to the outstanding properties of low density, high specific strength, excellent corrosion and oxidation resistance at high temperatures [5, 6], including Ti–Al, Fe–Al, Nb–Al, Ni–Al and TiAl–Nb [7–11]. Recently, Ti–Al intermetallics have been fabricated into porous materials by vacuum sintering technique from elemental powders, and the durability is highly depend on its pore structures

and pore-size distribution, which enable them good candidate for applications in filtration, solid–liquid separate and heat insulation [12–14].

Upon many researches, the pore formation mechanism of porous Ti–Al intermetallics was controlled by the reactive diffusion between titanium and aluminum particles, based on Kirkendall effect [12, 15, 16]. Jiang *et al.* [5] prepared titanium-aluminide membrane by more than 30 h sintering time with an average heating rate of 0.8 °C/min, and the pore formation mechanism was reported to be reactive diffusion. Hao *et al.* [12] produced super-light TiAl porous materials through a 23-h sintering process. It is necessary to mention that the major limitation of these researches is long sintering time and thus present a high energy consumption route. Yet there are researches which reported that the pore formation mechanism of porous Ti–Al materials depends on the thermal explosion (TE) reaction, accompanied by a large amount of heat release [17–19]. Contrary to Kirkendall effect, the bulk specimen was ignited by a constant heating rate and the reaction occurred over the whole specimen to the ignition temperature during TE [20]. The final products kept the original shape and avoided deformation and cracking due to the even heating of powder compacts. In addition, TE is a highly exothermic reaction, and hence has the advantage of low energy consumption, simplicity of equipment and short sintering time [3]. Wang *et al.* [19] prepared porous TiAl-based intermetallics via TE with high open porosity of 84%, and the total sintering time only took about 6 h. Porous TiAl₃ intermetallics have the higher oxidation resistance in Ti–Al system, compared to Ti₃Al and TiAl phases and relative low density [3, 18, 21]. Shi *et al.* [18] studied the effect of Ti/Al molar ratios on pore structures of porous Ti–Al intermetallics, and the specimen with Ti/Al molar ratio of 1:3 showed excellent high-temperature oxidation resistance at 650 °C. Those studies focused more attention about the influence of sintering factors on the pore structures and combining with pore-forming agent to prepare the high porosity of porous Ti–Al materials. The formation of these pores was simply attributed to one reaction mechanism. Additionally, in our previous work, three sizes of pores appeared in the final TiAl₃ skeletons, ranging from a few microns to hundreds of microns, while the sources of these pores were not fully verified and the pores generated by diffusion reaction or TE were not clear. Meanwhile, we have also explored other kinds of pore structure existed in the sintered products at the same sintering condition and they are somewhat different in shape and size compared to previous result [22]. Therefore, it is necessary to analyze the formation mechanism of these pores and its microstructure evolution process in different sintering stages as well as the respective contributions to

the porosity, in order to provide some thinking for later research such as control the pore structures and further improve the integral performances.

In the current work, we focus on the pore formation mechanism of porous TiAl₃ intermetallics prepared by elemental powder reactive synthesis with a nominal composition of Ti–75Al at.%. In addition, three sintering conditions were designed in this work, in order to study the expansion behaviors, phase compositions and pore structures at different sintering temperatures.

2 Materials and Methods

Elemental Ti (45 µm, 99.6% purity) and Al (25 µm, 99.95% purity) powders were used as reactant materials, and the powders were blended in a planetary ball mill at 450 r/min for 4 h, with a nominal composition of Ti–75Al at.%. Then, cylindrical green compacts were prepared in a stainless steel mold with 16 mm in diameter and 2~3 mm in height, and the uniaxial pressure was set to 300 MPa. Figure 1 shows the surface morphology of green compact, observing that the aluminum particles were evenly distributed around the titanium particles. Subsequently, the compacted disks were sintered in vacuum atmosphere (4.5×10^{-2} MPa). The sintering procedure is illustrated in Fig. 2, in which three sintering conditions were selected in this experiment and four samples were obtained, corresponding to the green compacts (Sample 0), sintered disks after 600 °C for 1 h (Sample 1), heating to an obvious TE phenomenon (Sample 2) and then heating up to 1100 °C for 1 h (Sample 3). The heating rate was set to 5 °C/min during the whole sintering cycle. Meanwhile, the same experiment was carried out in the tube furnace in a flowing argon atmosphere to confirm the existence of TE reaction, and a pair of WRe3–WRe25 thermocouples was placed between two specimens to record the actual temperature–time curve.

Open porosity is an important factor to characterize the pore structure and refers to the opening pores' volume occupied the proportion of the total volume of the sintered billet. The open porosity in this experiment was measured by Archimedes principle [15, 21] according to the expression: $\theta = (M_2 - M_1) / \rho_0 V$, where M_1 and M_2 are the mass of porous bodies in air and filled with vacuum pump oil, respectively, V is the external volume of porous samples and ρ_0 is the density of vacuum pump oil. The final products were identified by X-ray diffraction (XRD) using a Bruker D8 ADVANCE X-ray diffraction machine with Cu target ($\lambda = 0.15406$ nm), radiation at 40 kV and 150 mA settings. Differential scanning calorimeter (DSC) was used to analyze the heat release of the sample between 400

Fig. 1 Surface morphology of green compact

Fig. 2 Schematic illustration of sintering procedure

and 800 °C with the heating rate of 5 °C/min. Microstructures observations were performed by Quanta 250 scanning electron microscope (SEM) equipped with UANTAX400 energy dispersive spectrometer (EDS) to examine the elemental analysis.

3 Results and Discussion

3.1 Characteristics of Temperature Profile and Heat Release

Figure 3 shows the actual temperature profile of Ti–75Al at.% powder compacts during sintering. At the beginning, the temperature of the specimen kept on a modest increase to the point C according to the heating rate of 5 °C/min, and thus, TE did not appear in AC stage. Afterward, the specimen temperature began to increase at a higher rate, and the CD stage was considered as an incubation period. Essentially, when the temperature approached to the ignition temperature of point C (668 °C), the

Fig. 3 Temperature–time profile of the Ti–75Al at.% powder compacts during sintering

specimen was ignited with large amounts of heat release, resulting in a sharp rise in temperature and reaching to the combustion temperature of point E (1244 °C). It indicates that TE phenomenon appeared at CE stage and the reaction lasted for 166s, from ignition temperature to combustion temperature. Furthermore, the total sintering time only took about 6 h, representing the shorter synthetic time of TE reaction than diffusion reaction [5, 12]. The small inset in the upper left of Fig. 3 shows the magnified section in the vicinity of the TE phenomenon, in order to observe the variation of temperature before TE. The specimen was rapidly cooled to the furnace temperature at EF stage. Careful observation revealed that the AC section can be divided into rising stage along with the furnace temperature (AB) and stable stage (BC) around the melting point of Al (660 °C). This can be explained by the endothermic effect representing the melting of Al overlaps the heat released from the specimen body [24]. In consequence, the actual temperature of specimen was almost suppressed and cannot see the rising trend.

Fig. 4 DSC curve of Ti-75Al at.% compact with the heating rate of 5 °C/min

Figure 4 shows the differential scanning calorimeter (DSC) result while heating the sample with the heating rate of 5 °C/min, revealing the thermal response during the sintering process. In DSC curve, there are two downward exothermic peaks and one upward endothermic peak with increasing temperature. The first gentle exothermic peak was detected and marked by blue dashed line as shown in Fig. 4, indicating the weak solid–solid reaction occurred before the melting point of aluminum [25]. Then, a small endothermic peak at 661 °C appeared on account of the melting of aluminum. Ye *et al.* [24] reported that the melting of Al transforms the reaction mechanism to a liquid–solid reaction, which proceeds at a much higher rate. Novoselova *et al.* [25] have studied the thermal response of Ti-50Al at.% powder using two different heating rates of 5 and 20 °C/min. They have found the obvious exothermic peak around the temperature range of 650–680 °C with a large amount of heat released. Therefore, the second intense exothermic peak (679 °C) occurred with a large amount of heat released due to the violent solid–liquid reaction, which is in agreement with the result of the temperature–time profile mentioned above. Besides, Sina *et al.* [3] have examined the phase compositions above the endothermic peak in the DSC plot, presenting the diffraction pattern contains the elemental peaks and small peaks occurred corresponding to the TiAl₃ intermetallics.

3.2 Phase Transformation

Figure 5 shows XRD results of three sintered disks. As can be seen, a small amount of TiAl₃ phase can be detected after 600 °C for 1 h (sample 1), which coexists with raw materials of Ti and Al phases. It can be concluded that the formation of TiAl₃ phase is due to the solid–solid reaction

Fig. 5 XRD patterns of Ti-75Al at.% Al powder compacts at different sintering conditions

between Ti and Al elements and the reaction occurred on the outskirts of Ti powders, which was in agreement with the results of Liang *et al.* [26] and Sienkiewica *et al.* [2]. They found that TiAl₃ phase formed at 600 °C and this compound formed prior than any other titanium aluminides. Meanwhile, Xu *et al.* [27] reported that the solubility of Al in Ti was 11.7 at.%, whereas the maximum solubility of Ti in Al was only 0.12 at.%, and therefore, TiAl₃ phase formed first around Ti particles on account of solid-phase reaction. It is of interest to note that when the sintering temperature rised to an obvious TE phenomenon, XRD pattern (sample 2) illustrates that TiAl₃ phase dominating the system with very small amount of Ti phase and no free Al peak was detected. This result suggested that once the specimen temperature reached to the melting point of Al, liquid Al rapidly reacted with Ti powder to form TiAl₃ phase that the liquid Al was consumed quickly, and the reaction mechanism transformed into an instantaneous solid–liquid sintering [28]. When the sintering temperature reached to 1100 °C for 1 h (sample 3), the synthesized products were only single-phase TiAl₃ and no other alloys or unreacted elements were observed, indicating that the reaction finished completely. This result was in agreement with previous researches, which the single-phase TiAl₃ was also obtained in the final products [3, 22].

3.3 Expansion Behaviors and Porosity

Figure 6 illustrates the macrographs of Ti-75Al at.% powder compacts before and after sintering. It was obvious that the expansion phenomenon took place during three sintering conditions, while the specimens retained the original cylindrical shape and no crack can be found. In addition, the expansion behaviors (radial, axial and

Fig. 6 Macroscopic expansion behavior of Sample 0: green compact; Sample 1: sintering at 600 °C for 1 h; Sample 2: heating to an obvious TE phenomenon; Sample 3: sintering at 1100 °C for 1 h after TE

Fig. 7 Expansion behaviors and open porosity of different sintering conditions fabricated by Ti–75 at.% Al powder mixtures

volume) of three sintered samples are plotted in Fig. 7. It is shown that the specimen sintered at 600 °C for 1 h had a slight volume expansion of 27.5% and the radial and axial expansion increased to 6.2 and 13.1%. It indicated that the diffusion reaction between Ti and Al elements occurred and triggered the Kirkendall effect [24]. Furthermore, it is noted that the volume expansion ratio increased sharply with increasing temperature to TE and reached to the maximum value of 69.3%, as well as the radial expansion of 16.8% and axial expansion of 24.1%. This can be ascribed to the remarkable change in specimen temperature from 668 to 1244 °C in a short time interval, and the volume experienced an increase by 1.61 times according to the Ideal Gas Law of $PV = NRT$. When sintered at 1100 °C for 1 h after TE, the expansion curves dropped to 49.6% (volume expansion), 13.8% (radial expansion) and 15.5% (axial expansion), owing to the vacancy migration and atomic diffusion at high temperature in the skeletons [26, 29].

Figure 7 also shows the open porosity of three sintered disks and explains the main pore formation mechanism. After sintering at 600 °C for 1 h (Sample 1), the open porosity was slightly increased to 32.8% compared to the green compact of 22.2%, on account of the reactive diffusion between Ti and Al elements. With increasing temperature to TE appears (Sample 2), the open porosity increased to 58.7%, which indicates that the pore formation mechanism starts to be dominated by the intense TE reaction. After that, the open porosity decreased to 51.2% at 1100 °C for 1 h (Sample 3). This results agrees well with the trend of expansion behaviors. In consequence, the pores of porous TiAl₃ intermetallics can no longer be formed through Kirkendall effect and mainly formed in TE process.

3.4 Pore Structures

The final pore morphology of porous TiAl₃ intermetallics (Sample 3) shown in Fig. 8, exhibiting a sponge-like skeleton structure and uniform macroscopic pores. The pores are interconnected and formed an open-cellular structure. As can be seen from Fig. 8a, a large number of big pores ($\sim 60 \mu\text{m}$) were found and evenly distributed in the final sintered disks. Greater magnification shows that a mass of small pores ($\sim 10 \mu\text{m}$) and circular tiny pores ($\sim 3 \mu\text{m}$) formed and can be easily seen from Fig. 8b and c. According to the EDS analysis (Fig. 8d) together with the XRD results (Fig. 5), it is confirmed that these skeletons are single-phase and porous TiAl₃ products. Similar results were also obtained in previous findings [22], and the former studies only analyzed the preparation and influence of macropores on pore structures. Furthermore, previous researches have largely concern about the sintering conditions of synthetic porous Ti–Al materials such as heating rate, compacting pressure, sintering temperature and content of raw materials [21, 23, 24, 26]. However, three types of pores formed during this sintering process, and their

Fig. 8 Pore morphology of porous TiAl_3 intermetallics sintered at 1100 °C for 1 h **a** low-magnification SEM image, **b** high magnification of small pores, **c** tiny pores, **d** EDS analysis for the selected point

existence positions were different (Fig. 8), namely large pores formed among the continuous skeletons, small pores remained between product particles and tiny pores existed in final skeletons. Apart from that, three sintering stages in this experiment correspond to low-temperature solid-state reaction, solid–liquid reaction in a higher temperature and high-temperature partial diffusion. The contribution of these reaction mechanisms to porous structures was distinct, which will be introduced in the following discussion.

The microstructures of the compact disks after lower sintering stages are shown in Fig. 9. It can be noted that many pores appeared when sintering at 600 °C for 1 h (Fig. 9a, b), in which these pores formed because of the different diffusion rates between two components in a diffusion couple [23]. Increase in the sintering temperature to TE reaction occurred (Fig. 9c, d), which is above the melting point of Al; then, the liquid Al existed and reacted with solid titanium by large amounts of exothermic heat released. The intense reaction completed in a very short

time, and aluminum has fully consumed and left behind lots of large pores at the sites originally occupied by the Al particles [31]. Meanwhile, the pores formed at 600 °C grow rapidly to large pores during TE process, and the volume of pores increased significantly after TE reaction, compared to the sintered billet after 600 °C for 1 h. It was noteworthy that some small pores also observed between the product particles after TE reaction and the combination of particles was relative loose, which are marked by red circles as shown in Fig. 9d.

3.5 Microstructure Evolution of Porous TiAl_3 Intermetallics

Figure 10 presents the back scattered electron (BSE) images regarding the microstructure evolution of porous TiAl_3 intermetallics at different sintering conditions. The phases in the BSE images were identified by the energy dispersive spectrometer (EDS). As shown in Fig. 10a, the white

Fig. 9 SEM photographs of sintered specimens **a, b** at 600 °C for 1 h and **c, d** heating up to TE with different magnification

regions represent Ti particles and the dark gray regions are Al particles. After sintered at 600 °C for 1 h (Fig. 10b), it can be seen that some Ti particles are surrounded by the gray diffusion layer, with large amounts of Al phase still existing in the specimen. According to EDS analysis together with XRD results, it can be regarded that these layers are TiAl_3 phases. This is the result of Kirkendall effect, and some pores are formed in this diffusion stage [26]. When the temperature heating to an obvious TE phenomenon (Fig. 10c), the Al particles disappear and more TiAl_3 phase are found. The pore size and open porosity increase significantly after TE process and formed interconnected channels and mainly inherited the sites originally occupied by the Al particles [23]. It is interesting to note that a few number of Ti particles remained in the sintered disks, which is in accordance with the XRD results (Fig. 4). As shown in Fig. 10d, only TiAl_3 phase can be detected and the skeletons become thicker and denser caused by the coalescence of some particles as the temperature increases to 1100 °C for 1 h. The small pores

between the product particles remained and formed into irregular-shaped pores among the skeletons, which can be seen from BSE image. In addition, a small amount of near-circular tiny pores were formed in the porous TiAl_3 skeletons. The appearance of these tiny pores can be attributed to the partial diffusion at high-temperature stage, aluminum in TiAl_3 phase diffuse rapidly to titanium, and resulting in lots of vacancy precipitated from TiAl_3 skeletons [32, 33]. At the same time, there is 3.81% volume reduction during the chemical reaction $\text{Ti} + 3\text{Al} \rightarrow \text{TiAl}_3$, and high-temperature sintering will result in the increase in density and closure of the pores [30]. Meanwhile, the small pores and tiny pores mentioned above were interconnected or partly connected and would develop into closed pores in high-temperature sintering process, thus reduced the open porosity. It can be inferred that such hierarchical pore structures and interconnected channels are advantageous for applications in filtration and catalyst supports, and high-temperature sintering can provide enough strength of the

Fig. 10 BSE images of porous TiAl_3 intermetallics with different sintering process: **a** green compact, **b** sintering at 600 °C for 1 h, **c** heating to an obvious TE phenomenon and **d** sintering at 1100 °C for 1 h after TE

Fig. 11 Pore formation model of porous TiAl_3 materials during vacuum sintering

sample and enable the sintered products more homogenization.

It is noteworthy that porous materials were made of a large number of pores and pore walls and the load were undertaken by pore walls when pressed on the porous

sample. As can be seen from Fig. 10, the thickness of pore wall becomes thinner with the increase in the porosity and resulting in the gradual decline of mechanical properties [34, 35]. Additionally, porous Ti–Al intermetallics are typical brittle materials and exist an inverse relationship between mechanical strength and porosity [36]. Ye *et al.* [24] carried out the compressive test as a function of compacting pressure and concluded that the increase in pressure on green compact will result in the higher sintering density as well as the lower porosity, meanwhile, the compressive strength will be improved.

According to the reactive synthesis of Ti–75Al at.% powders from room temperature to 1100 °C, the steps of the pore formation process can be described as shown in Fig. 11. They are as follows: (a) A certain volume fraction of intergranular pores in green compact formed by the cold processing procedure; (b) small amounts of Kirkendall pores formed through reaction diffusion when sintering at 600 °C for 1 h and led to a slight expansion of the compact; (c) after TE process, a large amount of large pores formed at the original positions of the Al particles by reason of the rapid liquid–solid reaction, resulting in an obvious expansion behavior and some small pores existed between the product particles and (d) some tiny pores formed when the sintering temperature increases to 1100 °C for 1 h and appeared the shrinkage effect.

4 Conclusion

Porous TiAl₃ intermetallics with interconnected channels were successfully prepared through Ti–75Al at.% elemental powders at different sintering temperatures. The actual temperature of compact disks began to increase around the melting point of aluminum, indicating that the sintering process is in the form of TE. Meanwhile, the sintered specimen experienced the maximum volume expansion of 69.3% and highest open porosity of 58.7% after TE process. The final product was only single-phase TiAl₃ intermetallics, signifying that the chemical synthesis was sufficient. The chemical reaction mechanism of TiAl₃ intermetallics is followed from Kirkendall diffusion at low temperature, TE reaction and homogeneous diffusion at high temperature. Meanwhile, the pore formation mechanism in porous TiAl₃ materials can be considered as: Some intergranular pores inherited from green compacts, small pores appeared between the loose product particles after TE reaction, large pores formed when the liquid aluminum appeared and some Kirkendall pores turned into large pores during TE process, and tiny pores precipitated from skeletons at high-temperature sintering.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

- [1] F. Wang, Y. Liang, S. Shang, *Mater. Des.* **83**, 508 (2015)
- [2] J. Sienkiewicz, S. Kuroda, R.M. Molak, *Intermetallics* **49**, 57 (2014)
- [3] H. Sina, S. Iyengar, *J. Therm. Anal. Calorim.* **122**, 1 (2015)
- [4] C. Ran, H.R. Zhang, H. Zhang, *Acta Metall. Sin. (Engl. Lett.)* **30**, 456 (2017)
- [5] Y. Jiang, C. Deng, Y. He, *Mater. Lett.* **63**, 22 (2009)
- [6] A. Saboori, M. Pavese, C. Badini, *Acta Metall. Sin. (Engl. Lett.)* **30**, 675 (2017)
- [7] G.L. Hao, Q.P. Xu, H. Wang, *Mater. Sci. Technol.* **32**, 1592 (2016)
- [8] H.Y. Gao, P.Z. Shen, *Adv. Powder Technol.* **26**, 882 (2015)
- [9] H. Sina, S. Iyengar, *J. Alloys Compd.* **628**, 9 (2015)
- [10] W. Zhai, X. Shi, K. Yang, *Acta Metall. Sin. (Engl. Lett.)* **30**, 576 (2017)
- [11] Z.G. Lu, J. Wu, R.P. Guo, *Acta Metall. Sin. (Engl. Lett.)* **30**, 621 (2017)
- [12] G. Hao, H. Wang, X. Li, *Mater. Lett.* **142**, 11 (2015)
- [13] M. Kobashi, S. Miyake, N. Kanetake, *Intermetallics* **42**, 32 (2013)
- [14] H. Dong, P. Gao, G. Ye, *Mater. Struct.* **50**, 154 (2017)
- [15] C.L. Yeh, W.E. Sun, *J. Alloys Compd.* **669**, 66 (2016)
- [16] Y.H. He, J. Jiang, N.P. Xu, *Adv. Mater.* **19**, 2102 (2007)
- [17] O.D. Boyarchenko, O.K. Kamynina, A.E. Sytshev, *High-Temp. Synth.* **19**, 285 (2010)
- [18] Q. Shi, B. Qin, P. Feng, *RSC Adv.* **5**, 46339 (2015)
- [19] Z. Wang, X. Jiao, P. Feng, *Intermetallics* **68**, 95 (2016)
- [20] M. Adeli, S.H. Seyedein, M.R. Aboutalebi, *J. Alloys Compd.* **497**, 100 (2010)
- [21] Q. Peng, B. Yang, L. Liu, *J. Alloys Compd.* **656**, 530 (2016)
- [22] X. Jiao, X. Wang, X. Kang, *Mater. Lett.* **181**, 261 (2016)
- [23] H. Gao, Y. He, P. Shen, *Intermetallics* **17**, 1041 (2009)
- [24] S. Ye, H. Hao, W. Mo, *J. Alloys Compd.* **673**, 399 (2016)
- [25] T. Novoselova, S. Celotto, R. Morgan, *J. Alloys Compd.* **436**, 69 (2007)
- [26] Y. Liang, F. Yang, L. Zhang, *Intermetallics* **44**, 1 (2014)
- [27] L. Xu, Y.Y. Cui, Y.L. Hao, *Mater. Sci. Eng. A* **435**, 638 (2006)
- [28] Y.H. Wang, J.P. Lin, Y.H. He, *J. Alloys Compd.* **456**, 297 (2008)
- [29] A. Paul, M.J.H.V. Dal, A.A. Kodentsov, *Acta Mater.* **52**, 623 (2004)
- [30] W. Wang, Z. Fu, H. Wang, *J. Eur. Ceram. Soc.* **22**, 1045 (2002)
- [31] S. Gedeavanishvili, S.C. Deevi, *Mater. Sci. Eng. A* **325**, 163 (2002)
- [32] D.J. Goda, N.L. Richards, W.F. Caley, *Mater. Sci. Eng. A* **334**, 280 (2002)
- [33] P. Feng, J. Su, Y. Zhou, *Rare Metal Mat. Eng.* **11**, 2721 (2015)
- [34] J. Xiao, G. Qiu, Y. Liao, *Rare Metal Mat. Eng.* **44**, 1724 (2015)
- [35] N. Takata, K. Uematsu, M. Kobashi, *Mater. Sci. Eng. A* **697**, 66 (2017)
- [36] G.L. Hao, Q.P. Xu, H. Wang, *Mater. Sci. Technol.* **32**, 1592 (2016)